Journal of the Royal Society of Western Australia, 79:123-129, 1996

A review of Pb-isotope constraints on the genesis of lode-gold deposits in the Yilgarn Craton, Western Australia

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Abstract

Archaean lode-gold deposits within the Yilgarn Craton of Western Australia have made a major contribution to world gold production over the last century. However, models for the genesis of this class of deposits, particularly aspects of fluid and solute sources, remain controversial and require specific tests of their veracity. A systematic study of the initial Pb-isotopic compositions of Yilgarn lode-gold deposits and potential source rocks for ore components places constraints on possible source regions, and hence genetic models of ore formation.

The inferred initial isotopic composition of Pb in Yilgarn ore deposits correlates with that of the crustal Pb in the rocks of hosting greenstone belts, but is independent of the hostrock to the deposit. Accordingly, the ore-deposit initial Pb-isotope compositions show regional variations with crustal rocks. These are inferred to vary with the age, composition and degree of metamorphic-magmatic depletion of the lower to middle crust, which is considered to be the source of Pb in the deposits. With the available geological constraints, the heterogeneous source can be modelled as follows; derivation from early Archaean ($\geq$3.7 Ga) crust which is metamorphically depleted and/or partially melted at *ca.* 3.3 Ga; further reworking from *ca.* 2.7 Ga; and then sampling of the Pb in this heterogeneous crust by auriferous fluids at *ca.* 2.63 Ga. The Pb isotope modelling of source regions is not unique, but requires that the ore deposit Pb has an older crustal component which varies systematically on a regional scale independent of the composition, metamorphic grade and age of crustal rocks. This constrains the source of Pb in lode-gold deposits to include a component from the high-grade mid- to lower-crust via either metamorphic or magmatic processes.

Introduction

Lode-gold deposits in the Yilgarn Craton account for much of the annual gold production in Australia (*i.e.* 175 tonnes Au in 1995). Understanding the mode of formation of such deposits is pivotal to discovering new unexposed deposits, and hence much effort has been directed towards the establishment of robust deposit models which are predictive. The isotopic composition of Pb in ore deposits may be used as a tracer of Pb sources, and hence help constrain mineralisation processes. To use Pb isotopes as a source tracer, it is important to determine; (i) the initial Pb-isotopic composition and age of the ore system, and (ii) the coeval Pb in potential sources in, or below, the terrain hosting the gold deposit.

Over the last decade, colleagues and students of the authors at the Key Centre for Strategic Mineral Deposits have utilised the joint mass spectrometer facilities at Curtin University as part of multidisciplinary research into lode-gold deposits. This contribution describes the role of Pb-isotope tracer studies in developing the current understanding of Archaean lode-gold deposit source-regions within the Yilgarn Craton of Western Australia.

Geological background

The Yilgarn Craton is composed of; (i) greenstone belts consisting of volcanic, sedimentary and intrusive rocks, which are typically metamorphosed and variably deformed, and (ii) complex granitoid-gneiss terrains which separate the greenstone belts (Gee *et al.* 1981). Almost all of the Yilgarn lode-gold production comes from areas within greenstone belts.

Mineralisation may occur in various styles, from breccia lodes, vein sets, laminated veins or shear zones and as disseminated lodes. However, there are a number of common characteristics of lode-gold deposits (summarised by Groves 1993; Groves *et al.* 1995); an epigenetic timing of mineralisation, varying broadly from syn-metamorphic in deposits hosted by mid-amphibolite to granulite facies rocks, to post-metamorphic in deposits hosted by greenschist to low-amphibolite facies rocks, a ubiquitous structural control on mineralisation with deposits commonly forming adjacent to secondary or higher order splays off major faults or shear zones, a gold-only element association where base metal enrichments are generally negligible and K, LILE, CO_2, Na or Ca are added to proximal wallrocks, an $H_2O \pm CO_2 \pm CH_4$, low-salinity ore fluid, and a range of crustal depths, from near surface (very low metamorphic grade) environments to granulite facies conditions, for gold mineralisation.

Age of lode-gold mineralisation

For Pb isotope modelling purposes, it is important to constrain the age of lode-gold mineralisation. As predicted by the crustal continuum model, Archaean lode-gold deposits of the Yilgarn Craton are broadly coeval at

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de Laeter Symposium on Isotope Science
Curtin University of Technology, Perth, 1995

2.64-2.63 Ga (Groves 1993). Although the available reliable data are few, Pb-Pb and Sm-Nd isochrons, mineral U/Pb ages and Ar-Ar plateau ages for hydrothermal or alteration minerals associated with mineralisation are broadly synchronous (Clark *et al.* 1989; Barnicoat *et al.* 1991; Wang *et al.* 1993; Kent 1994; Kent & McDougall 1995), although at least one major deposit (Mt Charlotte) may be 30 m.y. younger than the nearby Golden Mile mineralisation (Kent & McDougall 1995). In addition, age constraints provided by the youngest granitoids cut by lode-gold deposits and dykes which cut mineralisation are in agreement with the direct dating of mineralisation (*e.g.* Kent 1994; Bloem *et al.* 1995; Kent & McDougall 1995). Hence, for the Pb isotope modelling presented below, an age of 2.63 Ga is taken for mineralisation. In addition to the dating of the lode-gold deposits, relative timing criteria and age estimates for metamorphic and deformational events (McNaughton *et al.* 1990a) are also compatible with this age. Magmatic activity broadly synchronous with mineralisation includes suites of late granitoids in the Murchison Province (Wiedenbeck & Watkins 1993; Yeats 1996), and a suite of late granites within the granitoid-gneiss terrains of the southwestern Southern Cross Province (Qiu *et al.* 1995).

Lead reservoirs coeval with lode-gold mineralisation

Unlike ore systems where the initial Pb-isotope compositions can often be determined from ore sulphides, it is more difficult to determine the coeval Pb-isotope composition of the rocks which may represent the reservoirs for Pb contributing to the ore fluid. The only common mineral which may allow initial Pb-isotope ratios to be estimated is K-feldspar, which is generally restricted to granitoids. Other minerals and rocks have U/Pb>0 and hence their Pb-isotope ratios have changed since formation. However, these materials may be analysed, and knowing the age of mineralisation, allow constraints to be placed on their Pb-isotope ratios at the time of mineralisation.

Granitoids

Granitoids of the Norseman-Wiluna belt of the Eastern Goldfields Province of Western Australia have been analysed and data are shown in Figure 1. The estimated composition of crustal rocks within the belt at 2.63 Ga is based on the Pb in a synvolcanic VHMS deposit at Teutonic Bore, and granitoids at Stennet Rocks, both compositions recalculated from their formation age to 2.63 Ga (McNaughton *et al.* 1990a,b).

The initial Pb-isotope compositions of the granitoids, based on K-feldspar data, are divided into three groups (Fig 1). The main group shows all data constrained to within two 2.63 Ga isochrons shown as parallel lines, and with K-feldspar data concentrated towards the intersection of the crosscutting crustal line. This group includes all available data on granitoids which are intrusive into the greenstone belts north of the Victory mine, Kambalda. Towards the west and south of Kambalda, the granitoids fall above these parallel lines, whereas, towards the northeast and east in the Eastern Goldfields Province they fall below these lines (both open circles; Fig 1). For comparison, granitoid K-feldspar data from the Murchison and Southern Cross Provinces are also shown (open squares; Fig 1), and broadly overlap the granitoid trend in the Norseman-Wiluna belt.

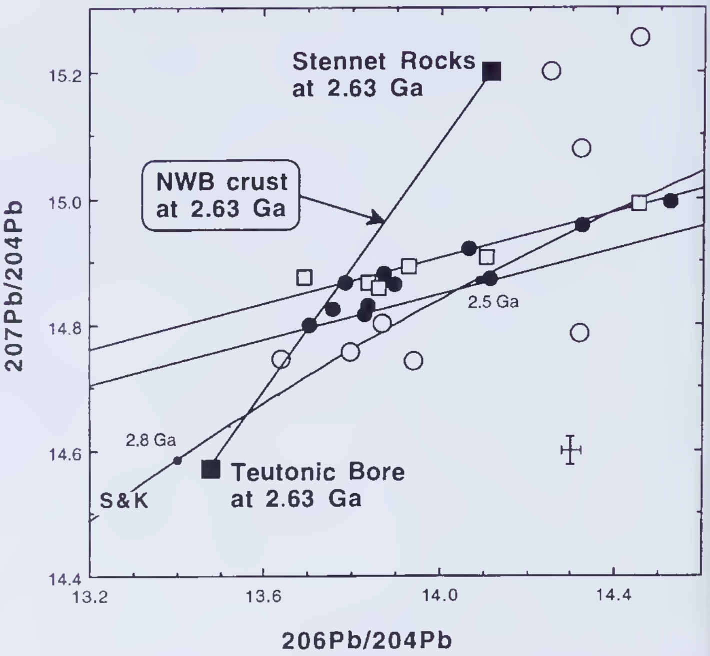

Figure 1. Common Pb-isotope plot showing K-feldspar data compared to the Stacey & Kramers (1975) lithospheric growth curve and the estimated composition of the crustal rocks of the Norseman-Wiluna belt (NWB) at the time of gold mineralisation (*i.e.* from Stennet Rocks to Teutonic Bore at 2.63 Ga; McNaughton *et al.* 1990b). Error bars are 2σ. Symbols; closed circles = NWB granitoids intrusive into greenstones north of Kambalda with 2.63 Ga isochrons bracketing these data; open circles (below parallel lines) = intrusive granitoids of the Northeastern Goldfields; open circles (above parallel lines) and Stennet Rocks = intrusive granitoids of the Norseman area and south of Coolgardie; open squares = Murchison and Southern Cross data. References; Oversby (1975). McNaughton & Bickle (1987), Perring & McNaughton (1992), Knight (1994). Wang *et al.* (1993), Ojala (1995), and unpublished data.

The granitoids of the northeastern Eastern Goldfields Province are interpreted to have a different source region to all other areas. The inferred boundary of this isotopically distinctive terrane approximately corresponds to the position of the Keith-Kilkinny lineament. Towards the south and west of Kambalda, older crustal rocks in the granitoid source regions have been inferred on the basis of isotopic data (Oversby 1975; Perring & McNaughton 1992).

Greenstones

The Pb-isotope data for lithologies within greenstone belts in the Norseman-Wiluna belt are shown in Figure 2. Relative to the estimated crust at 2.63 Ga and the main granitoid field (shown as parallel lines; from Fig 1), the rocks of the Norseman region plot largely above the granitoid data, whereas those of the Kambalda-Kalgoorlie-Mt Pleasant region plot below. These data are modern Pb-isotopic compositions. The Pb in each rock at the time of mineralisation is not known, but will plot along a 2.63 Ga isochron fitted to each data point but at a less radiogenic composition. Scatter in the data may be induced by open system behaviour of Pb-U between volcanism and modern times, but the general adherence of data to consistent fields suggests this effect is minor.

Therefore, the initial Pb-isotope ratios for the greenstones could lie on the 2.63 Ga crustal mixing line, slightly above and below the granitoid data.

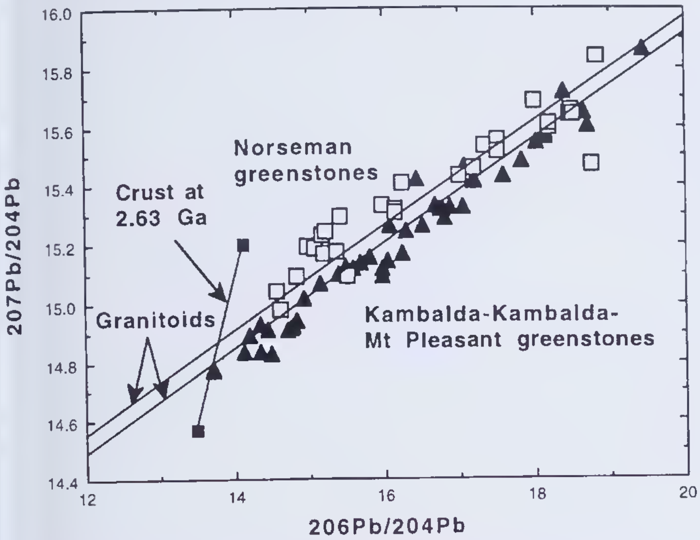

Figure 2. Common Pb-isotope plot showing the Norseman-Wiluna belt crustal mixing line and 2.63 Ga isochrons bracketing the granitoid Pb field (from Fig 1) compared to all greenstone data for the Kambalda-Kalgoorlie-Mt Pleasant region (triangles), and the Norseman region (squares). Data from; open squares (Perring & McNaughton 1992; McCuaig & McNaughton, unpublished data); closed triangles (Roddick 1983; Chauvel *et al.* 1985; McNaughton *et al.* 1988; Gebre-Mariam *et al.* 1993).

As with the granitoid data, the distinctly more radiogenic Pb in greenstones from the Norseman area, compared to the Kambalda-Kalgoorlie-Mt Pleasant area, represents a fundamental and provincial difference in the source of the Pb in both the greenstones and intrusive granitoids. The (gradational?) boundary between these different regions lies somewhere south of Kambalda and north of Norseman. Importantly, the southern part of the Norseman-Wiluna belt shows the most radiogenic Pb in both the granitoid and greenstone lithologies. To date, there are no published Pb-isotope data on greenstone lithologies from outside the Norseman-Wiluna belt.

Initial lead isotope composition of ore systems

The initial Pb of lode-gold ore systems is best determined from Pb-rich minerals genetically associated with the ore. Lead sulphide (galena) or tellurides are used, if they are present, but Fe-sulphides (pyrite, pyrrhotite) are more common and reliably preserve the initial Pb-isotope compositions in some cases (*e.g.* Ho *et al.* 1994). In a few cases, K-feldspar, sphalerite and scheelite associated with the ore have yielded reliable initial Pb-isotope ratios (Barnicoat *et al.* 1991; *unpublished data*).

Galena, with U/Pb = 0, is considered to be the best sampling medium to establish the initial Pb-isotope composition of lode-gold ore system. Galena occurs as a trace mineral in a proportion of lode-gold deposits. However, previous studies have shown that it does not always preserve the initial Pb of the ore system (*e.g.* Browning *et al.* 1983; Perring & McNaughton 1990; McNaughton *et al.* in press). Similarly, Pb tellurides may be used (Browning *et al.* 1983), but are rarer than galena. Iron sulphides are common ore-related minerals in the majority of deposits, and, with proper sampling methodologies (*e.g.* Ho *et al.* 1994), can yield the initial Pb-isotope ratios. For most deposits, a number of ore sulphide samples have been analysed and an assessment of the data must be made to determine if the initial Pb ratios are preserved. In deposits where a range of Pb-isotope compositions occur, the least radiogenic composition is taken as the best estimate of the initial Pb (*e.g.* Ho *et al.* 1994). More radiogenic compositions are attributed to *in situ* U-decay, from U either within the sulphide or within inclusions in the sulphide, or from more radiogenic Pb mobilised into the sulphide from an external source after sulphide formation. In the following discussion, only initial Pb-isotope compositions, which are inferred using the criteria discussed above and by McNaughton *et al.* (1990b) and Ho *et al.* (1994), are considered.

Figure 3 presents the initial uranogenic Pb-isotope ratios of deposits within the Norseman-Wiluna belt. The data form a linear array, and show provinciality *i.e.* a systematic change in Pb-isotope composition between geographic regions (Groves *et al.* 1995). The least radiogenic end of the array is represented by deposits to the north of the belt, whereas the most radiogenic data are from around Norseman at the southern end of the belt. These differences correlate with both the granitoid (Fig 1) and greenstone data (Fig 2) from these regions. Further, within some areas along the regional strike of the greenstone belts, the initial Pb-isotope ratios from deposits are invariant at the scale of >100kms (*e.g.* Mt Pleasant area to Kalgoorlie to Victory mine, Kambalda; McNaughton *et al.* 1993), whereas other areas show systematic changes on this scale (*e.g.* from Victory mine, Kambalda to Norseman; Fig 3). There is a weak correlation

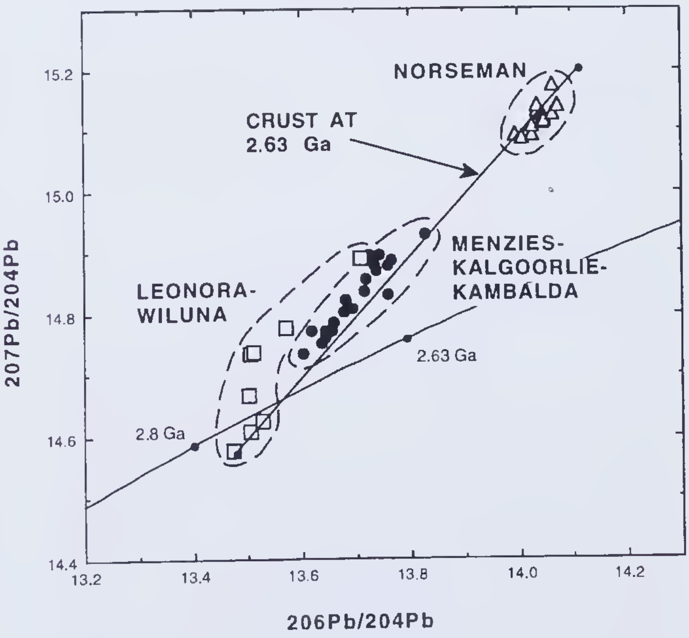

Figure 3. Common Pb-isotope plot showing the initial Pb for gold deposits from the Norseman-Wiluna belt, Stacey & Kramers (1975) growth curve and the crustal mixing line at 2.63 Ga from Fig 1. The gold deposit data fall into groups which correlate with geographical regions. Data from; McNaughton *et al.* (1990b, 1993) and Groves *et al.* (1995).

between initial Pb-isotope compositions of greenstone-hosted deposits and location across regional strike towards the granitoid-gneiss terrains (McNaughton *et al.* 1993). However, the initial Pb-isotope compositions for the deposits appears to be independent of hostrock (McNaughton *et al.* 1993; Ho *et al.* 1994).

The data for lode-gold deposits elsewhere in the Yilgarn craton are shown in Figure 4. There is a significant overlap with the Norseman-Wiluna belt data, although some deposits in the Murchison Province show significantly lower $^{206}Pb/^{204}Pb$ at similar $^{207}Pb/^{204}Pb$ (Fig 4). Griffin's Find in the Southern Cross Province is special in that the deposit occurs in the highest metamorphic grade setting of any deposit so far recognised (discussed below), and it is noteworthy that it has a similar initial Pb-isotope composition to other deposits (Fig 4).

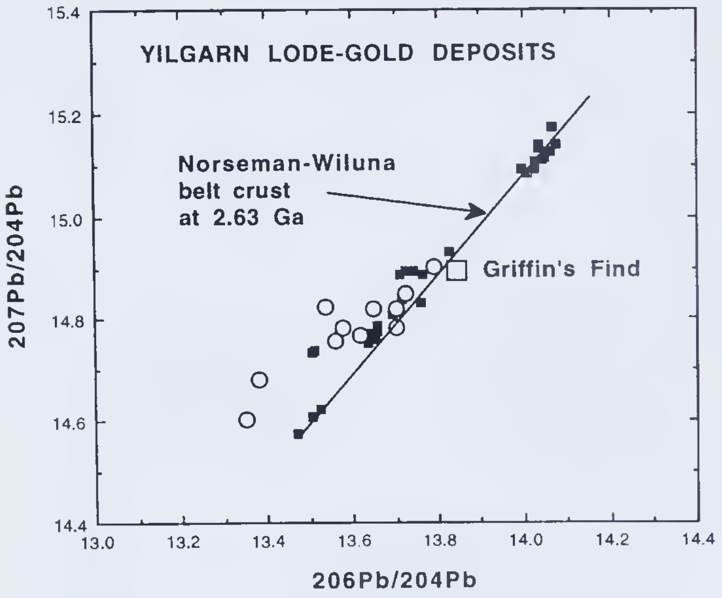

Figure 4. Common Pb-isotope plot showing the initial Pb for gold deposits from the Eastern Goldfields (closed squares), Murchison and Southern Cross Provinces (open circles, with Griffin's Find indicated), and the Norseman-Wiluna belt crustal mixing line at 2.63 Ga from Figure 1. Data from; McNaughton *et al.* (1990, 1993), Vielreicher *et al.* (1994) and Ojala (1995).

Discussion

Archaean Yilgarn Craton: Source of Pb in deposits of the Norseman-Wiluna belt

The initial Pb-isotope data from the lode-gold deposits of the Yilgarn craton (Fig 4) are compared with the estimated crustal Pb at the time of mineralisation in Figure 5. The ore deposit data for the Norseman-Wiluna belt correlate well with the 2.63 Ga crustal trend (Fig 3). As the crustal trend at 2.63 Ga is based on estimates of the Pb-isotope compositions of exposed upper crustal rocks, it could be inferred that the source of Pb in the deposits is also from the same upper crustal reservoir. However, the radiogenic endmember of the 2.63 Ga crustal trend is represented by a granitoid which undoubtedly attained its initial Pb from its lower to middle crustal source. Similarly, the lower granulite facies deposit at Griffin's Find in the Southern Cross Province (Barnicoat *et al.* 1991) also has an initial Pb-isotope composition close to this crustal trend (Fig 4), suggesting that both the upper and mid-lower crust in the craton were broadly similar in their Pb-isotope characteristics at 2.63 Ga. Similarly, the overlap of Pb-isotope data from deposits from the Murchison, Southern Cross and Eastern Goldfields provinces (Fig 4) suggests that this heterogenous upper-lower crustal source of Pb found in the gold deposits occurs on a regional scale, and that mineralisation was broadly coeval on this scale.

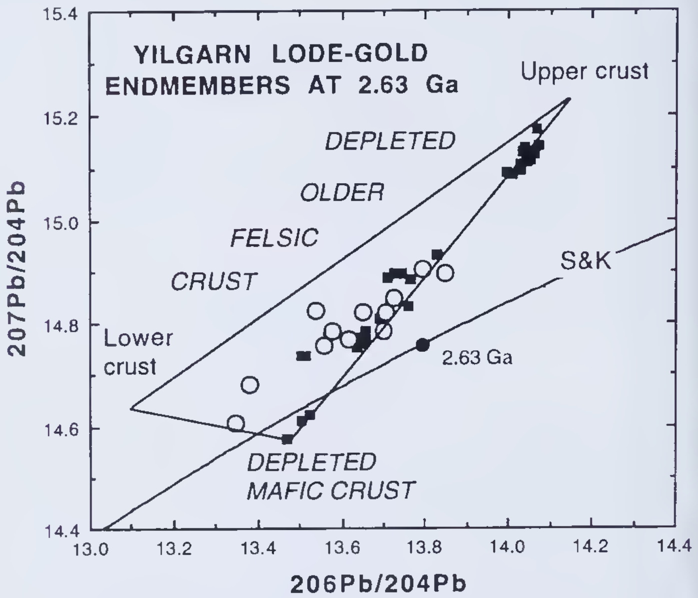

Figure 5. Common Pb-isotope plot showing the ore-deposit initial Pb-isotope compositions from Figure 4, and the inferred crustal endmembers (modified from McNaughton *et al.* 1990b).

The radiogenic nature of Pb from deposits, greenstones and granitoids of the Norseman region, compared to other regions, implies that all owe their Pb characteristics to a common source. Given that zircon xenocrysts and cores to *ca.* 2.7-2.63 Ga magmatic zircon grains within granitoids from this region and other parts of the Yilgarn have ages up to 3.5-3.3 Ga (Hill *et al.* 1989; Qiu *et al.* 1995), the preferred explanation of the Norseman radiogenic signatures is that they are due to older crustal rocks underlying this region (*cf* Oversby 1975; Campbell & Hill, 1988). This radiogenic Pb signature can be modelled (see below) and must include a significant period of evolution, prior to 2.63 Ga, with enhanced U/Pb, typical of upper crustal rocks.

The least radiogenic endmember of the 2.63 Ga crustal trend, and overlapping data for lode-gold deposits (Fig 5), fall close to the global lithospheric growth curve of Stacey & Kramers (1975), but at model ages significantly older than the age of mineralisation (McNaughton *et al.* 1990a). Assuming that the lithospheric growth curve is valid, this implies that the Yilgarn craton has not evolved like typical Archaean crust (*e.g.* Richards 1983), and includes a stage of retarded Pb-isotope growth prior to 2.63 Ga. Modelling of potential sources to achieve the observed results yield an infinite number of solutions, and other geological constraints must be applied. The simplest model requires older felsic crust undergoing high grade metamorphism and depletion of U with respect to Pb, at least a few hundred million years prior to mineralisation. This process would produce the Teutonic Bore endmember Pb (of the crustal trend) at 2.63 Ga with an older model Pb age (Fig 3). As the radiogenic endmember of the Norseman-Wiluna Belt 2.63 Ga crustal trend also requires an older crustal source, it follows that all the Pb from the 2.63 Ga crustal trend in Figure 5 requires an older crustal component at 2.63 Ga.

The greenstone data (Fig 2) do not show the large variation recorded in either the crustal trend or the ore deposit data. Assuming the outcropping greenstones are representative of greenstones at deeper levels, it follows that the greenstones cannot be the dominant source of Pb in the deposits. A deep source of Pb (*i.e.* below the greenstones) for the lode-gold ore deposits from underlying crust isotopically similar with the granitoids must be inferred at 2.63 Ga. A deep source of Pb in the deposits is also compatible with the observation that the initial Pb is independent of hostrock composition and crustal depth of mineralisation (*i.e.* depths corresponding to lower granulite to subgreenschist facies metamorphic conditions), as well as the epigenetic timing and ubiquitous relationship of deposits to splays of major faults and shear zones, which could allow ore fluids from deeper levels to access the entire crustal section.

Archaean Yilgarn Craton: Source of Pb in all deposits

The ore-deposit initial Pb data from the entire Yilgarn Craton are also shown in Figure 5 with estimated compositions of crustal reservoirs. The Pb mixing trend at 2.63 Ga for the crustal rocks of the Norseman-Wiluna belt in Figure 5 is interpreted to represent mid-lower to upper crustal Pb from older crust. The radiogenic endmember reflects a growth stage with enhanced U/Pb (*i.e.* enriched or upper crustal Pb), whereas the other end is from depleted or mid-lower crust with low U/Pb and retarded Pb-isotope growth.

Data falling significantly to the left of this trend in Figure 5 come from the northern Yilgarn Craton (*i.e.* north of Leonora in the Norseman-Wiluna Belt and the northern Murchison Province), and require an additional Pb component which has experienced retarded growth in ^{206}Pb/^{204}Pb with respect to ^{207}Pb/^{204}Pb, compared to the other data. However, the timing of the inferred U-depletion event cannot be the same as that producing the Norseman-Wiluna belt crustal and deposit trend at 2.63 Ga. At the time of gold mineralisation, Figure 5 shows the trend for crust which is 3.3 Ga old and was variably depleted-enriched (*i.e.* lower and higher U/Pb, respectively) at *ca.* 3.3 Ga. This crustal array has been fitted to the upper end of the Norseman-Wiluna belt crustal array at 2.63 Ga to essentially define the second side of a triangle of Pb-isotope compositions which enclose all initial Pb-isotope compositions for the ore deposits in Figure 5. The slope of the upper side of the triangle is defined by the ages for t_1 and t_2 (*i.e.* 3.3 and 2.63 Ga, respectively; see McNaughton 1987).

To obtain crustal Pb-isotope compositions significantly above the lithospheric growth curve requires crust older than 3.3 Ga which evolves up to 3.3 Ga with an enhanced U/Pb (*i.e.* as upper crust). Modelling granitoid source regions suggests that this crust is at least 3.7 Ga old (Cassidy & McNaughton, *unpublished observations*). This is approximately the age of the oldest crustal segment known in the Yilgarn Craton (Kinny *et al.* 1990), and 3.7 Ga is used in the modelling (shown in Fig 6) as the age of the protocrust underlying the Yilgarn craton.

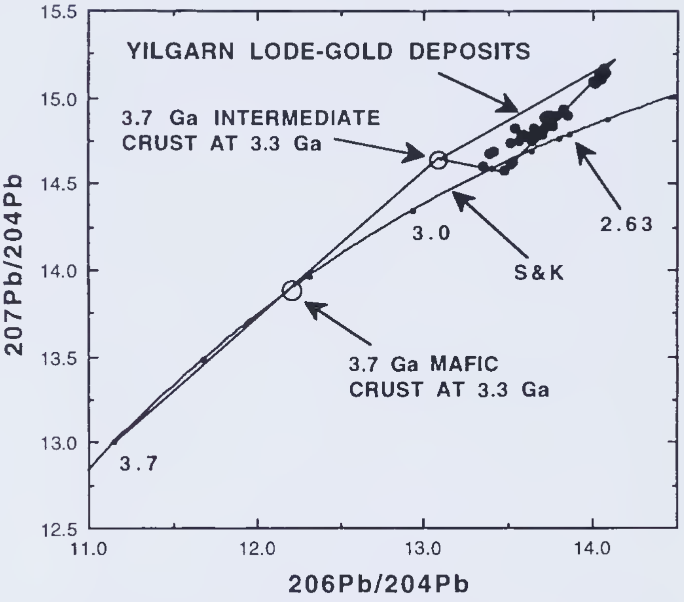

Figure 6. Common Pb-isotope plot showing the evolution of Pb from 3.7 Ga crust to produce the trianglar field of crustal Pb-isotope compositions at 2.63 Ga, which encompasses the Yilgarn ore-deposit initial Pb-isotope compositions shown in Fig 5.

The triangular field for Pb-isotope compositions shown in Figure 5 can be modelled by forming a mafic-intermediate crust at *ca.* 3.7 Ga. The intermediate component is interpreted to have evolved with an average U/Pb higher than the Stacey & Kramers (1975) growth curve, whereas the mafic components remained near the lithospheric growth curves (*i.e.* U/Pb near the average lithosphere) until about 3.3 Ga, at which time the 3.7 Ga crust was variably depleted (*i.e.* metamorphosed-partially melted) in U with respect to Pb. On average, the mafic components are interpreted to have experienced an overall lowering of U/Pb, leading to retarded Pb-isotope growth from 3.3 Ga until 2.63 Ga, and produced compositions near, but slightly below, the growth curve, and to the left of the Stacey & Kramers lithosphere at 2.63 Ga (Fig 6; represented by the Teutonic Bore data in Fig 3). The 3.7 Ga old crustal components of intermediate composition must have evolved well above the Stacey & Kramers growth curve by 3.3 Ga (Fig 6), and were then variably depleted during the 3.3 Ga event, producing the upper side of the inferred trianglar field in Figures 5 and 6 by 2.63 Ga. The average U/Pb of the intermediate crust must have been lowered to less than that of the mafic crust during the 3.3 Ga event, probably due to the preferential partial melting of the intermediate crust. This is interpreted to have produced very retarded Pb-isotope growth of the intermediate crust between 3.3. and 2.63 Ga.

The modelling described above allows for timing constraints of known and inferred formation ages of Yilgarn rocks and events. However, in detail, the modelled U/Pb for the post-3.3 Ga crust is unusually low, and the U/Pb of the 3.7 Ga intermediate crust prior to 3.3 Ga is unusually high. Both these anomalies would be lessened if the initial crust was older than 3.7 Ga, and/or the major depletion event was older than 3.3 Ga. The inferred *ca.* 4.2 Ga felsic crustal rocks of the northwestern Yilgarn (Kinny *et al.* 1990), and the presence of 3.3-3.5 Ga zircon xenocrysts in granitoids, indicate that such alternative models are feasible.

Conclusions

Lead isotope data from Yilgarn lode-gold deposits and presently exposed rocks may place important constraints on the crustal evolution and metallogenesis of the craton. Modelling of Pb-isotope compositions of rocks and ores within the known and partly inferred temporal framework of the craton can yield an infinite number of solutions. The Pb-isotope modelling suggested in this review (Fig 6) suggests that the Yilgarn craton is underlain by crustal rocks which may be >3.7 Ga old. This old crust comprised both mafic and intermediate components which evolved to form heterogeneous crust by the time of a major depletion event (metamorphism-partial melting) at *ca.* 3.3 Ga or older. Thereafter, the depleted crust evolved to produce Pb-isotope compositions at 2.63 Ga, the time of broadly coeval gold mineralisation across the craton, which lie within a trianglar field of Pb-isotope compositions on a ^{207}Pb/^{204}Pb vs ^{206}Pb/^{204}Pb diagram, defined by crustal components with different geochemical compositions and histories. The initial Pb-isotope compositions of the gold deposits closely adhere to this triangular field, and, together with geological constraints, are best interpreted to indicate that all deposits obtained their Pb mostly from the older depleted crust at mid to lower crustal levels. This conclusion is compatible with a crustal continuum of deposits (Groves 1993) from granulite to subgreenschist facies settings, a ubiquitous spatial association with major crustal-scale shear or fault zones, the occurrence of deposits in all rock types and a similarity of geochemical and ore fluid characteristics on a craton scale (Ho *et al.* 1992; McNaughton *et al.* 1992, 1993). The deep source of Pb constrains the fluid source to high metamorphic grade regions, and implies that mineralisation resulted from either high grade metamorphic or deep magmatic processes.

Acknowledgements: This summary reflects a decade of research by many past and former members of the Key Centre for Strategic Mineral Deposits and it precursors; all are thanked. Special thanks go to M Dahl for technical assistance, the Curtin University mass spectrometrists, particularly W Chisolm, I Fletcher and K Rosman, continued funding from UWA, Curtin and ARC, and finally, and most importantly, to John de Laeter whose foresight and energies were instrumental in establishing the world-class mass spectrometry facilities in Western Australia.

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